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Comparing the Robustness of High-Frequency Traveling-Wave Tube Slow-Wave Circuits

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Summary

A three-dimensional electromagnetic field simulation software package was used to compute the cold-test parameters—phase velocity, on-axis interaction impedance, and attenuation—for several high-frequency traveling-wave tube slow-wave circuit geometries. This research effort determined the effects of variations in circuit dimensions on cold-test performance. The parameter variations were based on the tolerances of conventional micromachining techniques.

Introduction

At frequencies greater than 90 GHz, vacuum electronic amplifiers have potential for high-data-rate secure communications, surveillance, and remote sensing. However, the helical slow-wave circuit geometry commonly used at lower frequencies becomes less practical in this regime where small circuit dimensions make conventional fabrication and assembly techniques (ref. 1) very difficult. Alternatively, high-frequency (>90 GHz) slow-wave circuits call for circuit geometries that are compatible with micromachining techniques such as folded waveguide or vane-type circuits. In addition, dimensional variations resulting from manufacturing tolerances can be large enough to cause variation and serious degradation in performance. Thus, it is important to determine the sensitivity of various geometries to these manufacturing tolerances. This allows a traveling-wave tube (TWT) designer to choose a slow-wave circuit that is robust to fabrication tolerances resulting in predictable performance. The study presented in this report modeled three TWT geometries, incorporating dimensional variations, and determined their corresponding robustness.

The TWT slow-wave circuit geometries were modeled and designed with the commercial software CST MICROWAVE STUDIO (MWS) from CST—Computer Simulation Technology (ref. 2). MWS is a Microsoft Windows-based, three-dimensional, electromagnetic field simulation software for the analysis and design of components such as antennas, filters, transmission lines, couplers, and resonators. The simulations described in this report use the eigenmode solver to calculate the modal field distributions of the TWT slow-wave circuits. Periodic boundaries were used to calculate the cold-test characteristics: phase velocity, on-axis interaction impedance, and attenuation. Macros were written in Microsoft's Visual Basic for Applications to automatically calculate the cold-test characteristics. The accuracy and efficiency of MWS for simulating traveling-wave tube cold-test parameters has previously been established in reference 3.

Simulation

Three circuit geometries were selected for investigation based on their compatibility with micromachining techniques at millimeter-wave frequencies: folded waveguide (ref. 1), trapezoidal open vane (ref. 4), and rectangular enclosed vane, as shown in figures 1(a), (b), and (c), respectively. The folded waveguide is a fundamental backward wave circuit in which the RF (radiofrequency) wave couples with the electron beam in the phase shift range of 180° to 360°, while the vane geometries are fundamental forward wave circuits in which the wave couples with the beam in the phase shift range of 0° to 180° (ref. 1). The dimensions were designed such that the corresponding amplifiers operate at 20 kV and 94 GHz.

A single geometric period of each circuit is simulated with periodic boundaries in the axial direction. For the fundamental forward wave vane circuits, a geometric period is equal to the electrical period L of figures 1(b) and (c). However, for the fundamental backward wave folded waveguide circuit, two electrical periods $2L$ of figure 1(a) must be simulated to create a geometric period. Note that a geometric period represents the full circuit geometry as would be repeated in the axial direction. A range of phase shifts $\beta_n L$ are entered into the software, which then calculates the corresponding eigenmode frequency f for each. The axial phase constant of the nth space harmonic is β_n. Because one geometric period of the folded

waveguide TWT contains two electrical periods, each simulation will provide two eigenfrequencies symmetrically placed on the dispersion diagram. If the entered phase shift is $\beta_n L$, the frequencies will correspond to $\beta_n L/2$ and $[360 - (\beta_n L/2 - 180)]$ on the mode diagram. For example, if a phase shift of 400° is entered, the first two eigenfrequencies correspond to $\beta_n L$ = 200° and 340°.

Analysis

Normalized phase velocity (ref. 1), υ_p/c, is calculated by

$$\frac{\upsilon_p}{c} = \frac{2fL(180)}{\beta_n Lc} \tag{1}$$

where c is the free-space speed of light in meters per second.

On-axis interaction impedance (ref. 5), K_n, is calculated by

$$K_n = \frac{E_n^2}{\beta_n^2 P_{RF}} \tag{2}$$

where E_n is the beam on-axis electric field magnitude of the n^{th} space harmonic and P_{RF} is the time-averaged power flow.

Attenuation (ref. 5), α, is calculated by

$$\alpha = \frac{4.343 P_L}{NP_{RF}} \tag{3}$$

where P_L is the powerloss in the conductors and N is the number of electrical periods modeled.

Results

Each of the three slow-wave circuits was simulated, and the phase velocity, impedance, and attenuation were calculated at 94 GHz. Additional simulations included independently increasing each parameter by 5 μm to determine the dependence of the cold-test characteristics on dimensional tolerances.

Each of the folded waveguide circuit's five parameters (fig. 1(a)) was varied. Phase velocity is most sensitive to L with a variation of 0.52 percent, impedance is most sensitive to the beam tunnel radius a with a variation of 2.87 percent, and attenuation is most sensitive to the length of the straight waveguide section l with a variation of 1.34 percent.

Secondly, each of the trapezoidal vane circuit's five parameters (fig. 1(b)) was varied. Phase velocity is most sensitive to the vane gap δ with a variation of 6.09 percent, impedance is most sensitive to L with a variation of 10.15 percent, and attenuation is most sensitive to the vane height h with a variation of 17.49 percent.

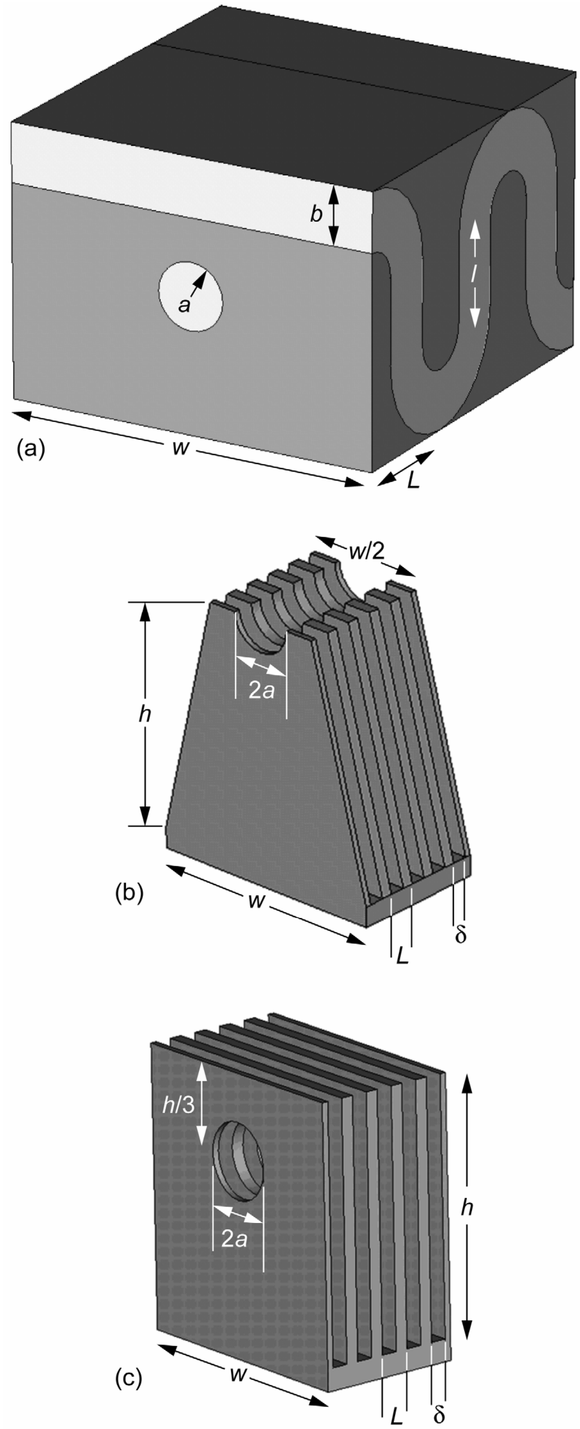

Figure 1.—Traveling-wave tube geometries. (a) Folded waveguide. (b) Trapezoidal open vane. (c) Rectangular enclosed vane.

TABLE I.—MAXIMUM ABSOLUTE VALUE OF EFFECT OF +5-μm DIMENSIONAL TOLERANCES ON VARIOUS SLOW-WAVE CIRCUIT GEOMETRIES

Circuit geometry	Change in normalized phase velocity, $\lvert\Delta\upsilon_p/c\rvert$, percent	Change in on-axis interaction impedance, $\lvert\Delta K\rvert$, percent	Change in attenuation, $\lvert\Delta\alpha\rvert$, percent
Folded waveguide	0.52	2.87	1.34
Trapezoidal vane	6.09	10.15	17.49
Rectangular vane	6.50	3.21	9.51

Lastly, each of the rectangular vane circuit's five parameters (fig. 1(c)) was varied. Phase velocity is most sensitive to *h* with a variation of 6.50 percent, impedance is most sensitive to *a* with a variation of 3.21 percent, and attenuation is most sensitive to *L* with a variation of 9.51 percent. A comparison of the three circuits' robustness is shown in table I.

Of the three geometries, the folded waveguide is the least sensitive to dimensional tolerances. It would therefore be useful to investigate its sensitivity in further detail. Several fabrication alternatives for the folded waveguide were investigated at mm-wave and THz frequencies including wire-EDM (electro-discharge machining) (ref. 6), x-ray LIGA (lithografie, galvanoformung, abformung), UV–LIGA, and deep reactive ion etching (DRIE) (ref. 7). Some micromachining techniques such as DRIE can keep tolerances to about 0.3 μm and are continually improving. However, there is usually an additional cost associated with increased accuracy because of increased fabrication time and complexity. Therefore, it is important to understand how the various tolerances affect performance, and weigh the tradeoffs between electrical performance and fabrication accuracy before choosing a fabrication technique.

Table II summarizes the effect of the dimensional tolerances for all five parameters of the 94-GHz, 20-kV folded waveguide circuit at the center frequency. The table shows that phase velocity is most sensitive to the parameter *L*, with as much as a 0.55-percent variation with a 5-μm tolerance. Impedance is most sensitive to the parameter *a*, varying by about 2.89 percent for a 5-μm tolerance, and attenuation is most sensitive to the parameter *a,* with a 2.23-percent variation for a 1-μm tolerance.

Conclusions

The dimensional tolerances of a folded waveguide and two vane-type traveling-wave tube circuits were investigated. For the folded waveguide, phase velocity is most sensitive to the electrical period *L* with a variation of 0.55 percent, impedance is most sensitive to tunnel radius *a* with a variation of 2.89 percent, and attenuation is most sensitive to the length

TABLE II.—EFFECTS OF DIMENSIONAL TOLERANCES OF 94-GHz, 20-kV FOLDED WAVEGUIDE CIRCUIT ON PHASE VELOCITY, IMPEDANCE, AND ATTENUATION

Dimension,[a] μm	Change in normalized phase velocity, $\lvert\Delta\upsilon_p/c\rvert$, percent	Change in on-axis interaction impedance, $\lvert\Delta K\rvert$, percent	Change in attenuation, $\lvert\Delta\alpha\rvert$, percent
Standard	0	0	0
$w - 5$	0.19	1.92	0.70
$w - 1$	.04	.38	.14
$w - 0.3$	.01	.11	.04
$w + 0.3$	.01	.11	.04
w + 1	.04	.38	.14
$w + 5$	.18	1.86	.68
$b - 5$	0.05	1.35	1.28
$b - 1$	.00	.21	.18
$b - 0.3$	.00	.06	.07
$b + 0.3$	.00	.06	.03
$b + 1$	.01	.22	1.32
$b + 5$	.03	.75	.38
$l - 5$	0.13	1.64	1.33
$l - 1$	.03	.54	1.69
$l - 0.3$	.01	.08	1.46
$l + 0.3$	.02	.26	.11
$l + 1$	.06	.95	1.00
$l + 5$	.15	1.21	1.34
$L - 5$	0.55	0.95	1.36
$L - 1$	.11	.18	1.48
$L - 0.3$	.03	.05	.01
$L + 0.3$	.03	.05	.03
$L + 1$	.11	.18	.03
$L + 5$	.52	.48	.12
$a - 5$	0.06	2.89	0.63
$a - 1$	.04	.58	.33
$a - 0.3$	.02	.22	.97
$a + 0.3$	.00	.02	1.69
$a + 1$	.01	.01	2.23
$a + 5$	.04	2.87	.85

[a]Dimensions are shown in figure 1(a), where *w* is the circuit width, *b* is the serpentine path thickness, *l* is the length of the straight waveguide section, *L* is the electrical period, and *a* is the beam tunnel radius.

of the straight waveguide section l with a variation of 2.23 percent. For the trapezoidal vane circuit, phase velocity is most sensitive to the vane gap δ with a variation of 6.09 percent, impedance is most sensitive to L with a variation of 10.15 percent, and attenuation is most sensitive to vane height h with a variation of 17.49 percent. Lastly, for the rectangular vane circuit, phase velocity is most sensitive to h with a variation of 6.50 percent, impedance is most sensitive to a with a variation of 3.21 percent, and attenuation is most sensitive to L with a variation of 9.51 percent.

Of the three geometries investigated, the folded waveguide circuit is the most robust, therefore showing the most promise for successful circuit fabrication and operation at high frequencies. However, very small impedance values for the folded waveguide necessitate long total circuit lengths, which make beam focusing more challenging.

Although the vane circuits are limited by their sensitivity to manufacturing tolerances, they have larger impedance values, which could result in a shorter, higher efficiency circuit. Micromachining techniques and their achievable tolerances continually improve, making vane circuits a promising alternative for the future.

Glenn Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 1, 2007

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14. ABSTRACT
A three-dimensional electromagnetic field simulation software package was used to compute the cold-test parameters--phase velocity, on-axis interaction impedance, and attenuation--for several high-frequency traveling-wave tube slow-wave circuit geometries. This research effort determined the effects of variations in circuit dimensions on cold-test performance. The parameter variations were based on the tolerances of conventional micromachining techniques.

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